

**Introduction:** The bulk chemical compositions of planets may yield important clues concerning planetary origins. Failing that, bulk compositions are still important, in that they constrain calculation of planetary mineralogies and also constrain the petrogenesis of basaltic magmas.

In the case of the Earth, there is little or no debate about the composition of the Earth's upper mantle. This is because our sample collections contain peridotitic xenoliths of that mantle. The most fertile of these are believed to have been little modified from their primary compositions. Using these samples and chondritic meteorites as a starting point, small perturbations on the compositions of existing samples allow useful reconstruction of the bulk silicate Earth (BSE) [1].

Elsewhere, I have argued that the next simplest case is the Eucrite Parent Body (EPB) [2]. Reconstructions based on Sc partitioning indicate that the EPB can be well approximated by a mixture of 20% eucrite and 80% equilibrium olivine. This leads to a parent body that is similar to CO (or devolatilized CM) chondrites. Partial melting experiments on CM chondrites confirm this model, because the residual solids in these experiments are dominated by olivine with minor pigeonite [3].

The most difficult bodies to reconstruct are those that have undergone the most differentiation. Both the Moon and Mars may have passed through a magma ocean stage. In any event, lunar and martian basalts, unlike eucrites, were not derived from undifferentiated source regions. Reconstructions are primarily based on compositional trends within the basalts themselves with some critical assumptions: (i) Refractory lithophile elements (Ca, Al, REE, actinides) are presumed to be in chondritic relative abundances; and (ii) some major element ratio is believed to exist in a chondritic ratio (e.g., Mg/Si, Mg/Al). The most commonly used parameter is Mg/Si.

**The Moon as an Example:** Several different attempts have been made to calculate the Moon's bulk composition. They generally fall into two classes: (i) Earthlike, but with a lower Mg#; or (ii) Refractory-enriched. The defenders of the Earthlike models have been Ringwood et al. (R) [4], O'Neill [5], and Jones & Delano (J&D) [6]. The chief defenders of a refractory Moon are Taylor (T) [7] and Muller et al. [8]. Further, J&D [6] showed that the large differences in calculated bulk compositions

were directly attributable to the choice of Mg/Si ratio for the bulk Moon (BSM). When projected from olivine, the BSM's of R and T are virtually indistinguishable. Taylor assumed that the Moon has a low Mg/Si (0.93), whereas R assumed that the Moon had a terrestrial Mg/Si ratio (1.09). Therefore, for reasons that were not totally clear, a less than 20% change in Mg/Si resulted in a 60-70% change in the concentrations of refractory lithophiles. Clearly then, the choice of boundary conditions is of utmost importance to the calculation and its result (Table 1). Calculations also show that changes in Mg/Si produce disproportional changes in Ca, Al, and Ti concentrations.

**TABLE 1**  
**ESTIMATES OF BULK LUNAR COMPOSITION**

	<u>Taylor</u>	<u>Jones &amp; Delano</u>	<u>Ringwood et al.</u>
SiO <sub>2</sub>	44.4	42.6	43.2
TiO <sub>2</sub>	0.3	0.19	0.30
Al <sub>2</sub> O <sub>3</sub>	6.1	3.7	3.7
Cr <sub>2</sub> O <sub>3</sub>	0.6	—	0.32
FeO	10.9	13.6	12.2
MnO	0.15	0.19	0.16
MgO	32.7	37.1	36.8
CaO	4.6	3.0	3.0
Sum	99.8	100.4	99.7
Mg/Si	0.92	—	1.09
Mg/Al	6.0	11.4	11.3

Although J&D's calculation agreed substantially with that of Ringwood et al., they did not constrain their calculation using Mg/Si, but instead opted for a CI Mg/Al ratio. Their reasoning was that Si tended to be more volatile than Mg or Al and that the variation in chondritic Mg/Si was marginally larger than for Mg/Al. However, because of the sensitivity of the calculation to the exact choice of Mg/Si ratio, I have explored the calculation's dependence on the choice of Mg/Al as well. The results are given below.

**BSM as a Function of Bulk Mg/Al:** The J&D composition given in Table 1 is simply one of many that these authors calculated. The composition given here is their "Intermediate Model," which was calculated to make a lunar magma ocean 500 km deep, thereby being consistent with lunar seismology and the multiple saturation points of pristine lunar

**TABLE 2**  
**SENSITIVITY OF BSM TO CHOICE OF Mg/Al**

	<u>L</u>	<u>CI</u>	<u>CV</u>
	<u>Chondrite</u>	<u>Chondrite</u>	<u>Chondrite</u>
SiO <sub>2</sub>	42.4	42.6	43.2
TiO <sub>2</sub>	0.16	0.19	0.21
Al <sub>2</sub> O <sub>3</sub>	3.5	3.7	4.7
FeO	13.7	13.6	13.8
MgO	37.5	37.1	34.4
CaO	2.8	3.0	3.8
Sum	≅100	≅100	≅100
Mg/Al	12.2	11.4	8.3
Mg/Si	1.14	1.13	1.03

glasses [6]. The models in Table 2 are all variants of that Intermediate Model. The only difference between the various models is the choice of bulk Mg/Al.

Table 2 shows the results of varying the Mg/Al constraint over the range of observed chondritic Mg/Al. The take home message from Table 2 is that neither the concentrations of refractory lithophile elements nor the BSM is highly sensitive to choice of Mg/Al ratio. Changes in bulk composition are small and changes in the absolute concentrations of refractory elements vary proportionally with changes in Mg/Al. Therefore, I conclude that since *some* assumption about the bulk composition is required by all calculations, Mg/Al is a much more useful boundary condition than Mg/Si.

**Why?** The reason why bulk compositions are very sensitive to the choice of Mg/Si is not obvious. However, I give a rationalization that may be an actual reason or part of such a reason.

Consider a planet with a molar (Fe+Mg)/Si ratio of unity. The planet could be constructed totally from pyroxene and no Ca or Al would be needed. If Ca and Al were known to be present, in would be necessary to also make a small amount of olivine to produce the Si necessary to make augite and plagioclase.

However, if the (Fe+Mg)/Si ratio were less than unity, most bulk composition calculations would use that excess silica to produce augite and plagioclase in proportions such that the Ca/Al of the planet was chondritic. And a body with a presumed (Fe+Mg)/Si ratio of 0.8 would require twice as much Ca and Al than one with a (Fe+Mg)/Si ratio of 0.9. Therefore, small changes in Mg/Si can produce large changes in calculated Ca and Al contents.

But if Mg/Si is bad, why is Mg/Al good? Again, the real reason is unknown. However, I believe that, when Mg/Al is used as a boundary condition, the

proportions of both major and minor phases are constrained. The major mineral phases in a chondritic body will always be ferromagnesian (olivine, low-Ca pyroxene, perovskite, etc.), so Mg is important. Aluminum abundance controls the abundance of minor phases such as feldspar, garnet, and spinel. And because we strongly suspect that the Ca/Al ratio of a planet should be chondritic, constraining Al content constrains the Ca content as well. Therefore I believe that choice of Mg/Al as a boundary condition constrains the abundance of both major and minor mineralogies.

**Conclusions:** Calculation of bulk compositions of differentiated planets is, at best, difficult. Small changes in the choice of Mg/Si ratio (~20%) in these calculations can lead to large changes in calculated refractory lithophile element concentrations (~60-70%). Larger changes in Mg/Al ratio (~50%) lead to smaller changes in refractory element concentrations (30-35%). This is of some importance because, since there is minor, but real, variation in these parameters within the known chondrite suite, it is probable that there is also such variation between planets. Therefore, it is important that imposed boundary conditions need not be exactly correct.

**References:** [1] Jagoutz E. et al. (1979) *Proc. Lunar Planet Sci. Conf. 11<sup>th</sup>*, 2039-2050. [2] Jones J.H. (1984) *Geochim Cosmochim Acta***48**, 641-648. [3] Jurewicz A.J.G. et al. (1993) *Geochim Cosmochim Acta***57**, 2123-2139. [4] Ringwood A.E. et al. (1986) *Earth Planet. Sci. Lett.* **81**, 105-117. [5] O'Neill H. St. C. (1991) *Geochim Cosmochim Acta***55**, 1135-1157. [6] Jones J.H. and Delano J.W. (1989) *Geochim Cosmochim Acta***53**, 513-528. [7] Taylor S.R. (1982) *Planetary Science: A Lunar Perspective*. Pp. 481. [8] Muller S. et al. (1988) *J. Geophys. Res.* **93**, 6338-6352.